Features of parallel connection of power supplies

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***Abstract*— Features of parallel operation of DC/DC power supplies is under consideration. Analyze of methods of reduction of transient time and of dynamical dispersion of currents is performed. Using of digital load share bus for improving of output specifications of parallel connection of DC/DC converters is considered. Ways of reductions of number of feedback loops are investigated.**

***Index Terms* — current sharing, DC-DC power converters, digital control.**

I. Introduction

NOW days parallel connection of power supplies becomes common technique. Lots of firms provide power supplies with ability of parallel working, for example TDK-Lambda, Mean Well, Contron, Eaton, Power One, GE Energy (ex-Lineage) etc. Parallel connection of power supplies provides many benefits: power supply system becomes scalable, flexible, and redundant which means more reliable. Parallel connection reduces product line, which allows manufacturers to decrease cost and price of a product and tech support of customer have to maintain fewer types of devices.

The cost of all the benefits is additional feedback loop that adjusts currents of power supplies. This feedback loop is external for DC/DC and crossover frequency of this loop must be at least 1/5 of crossover frequency of power supply feedback loop thus transient response of system becomes slower. Practical value of current mismatch at steady state is 1 to 3% of nominal output current of one power supply, but during transient current mismatch is 10 to 20 %. A system integrator must keep in mind the mismatch: during transient power supply with maximum output current should not be overloaded. Current share feedback loop usually exerts upon voltage feedback loop so during current transient process output voltage has some oscillations.

Analog load share bus has a practical limitation of 10 to 16 blocks connected in parallel. Digital load share bus requires fast and reliable digital interface with collision resolving.

The propose of this paper is to introduce load share technique with digital load share bus and automatic master detection.

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II. Load share techniques.

Load share techniques divides [1] [2] into three branches: droop technique, master-slave technique and automatic technique.

A. *Droop of output voltage*

This is the simplest method of load share. In this case output voltage of individual power supply decreases when output current increases or in other word we program output impedance of a power supply. Thus it is an open loop technique.

Current mismatch for this method is fixed and is proportional to voltage mismatch between power supplies and inversely proportional to possible voltage droop. This is simple open loop method with poor current share and degradation of regulation. Yet this method can be easily applied for ready to use power supplies with external reference/track input and no feedback or load share input.

B. *Master-slave technique, dedicated master*

This method can be applied for DC/DC converters with current mode control. In this method one module is selected as master and its voltage feedback loop forces other modules (slaves) to act as current sources. In current mode control schemes output of a voltage (error) amplifier is proportional to load current. All modules having the same design will provide same current. Transient response of parallel connection of modules is equal to multiphase system.

However this method has certain drawbacks. Being parallel connected the method is not redundant for malfunction of master module affects on slave modules. Wideband output of voltage error amplifier can easy pick-up spikes so for distributed systems peak current mode control becomes hardly possible.

C. *External controller*

External controller also is useful method for current sharing. External controller compares load current signal from power supplies and adjusts corresponding feedbacks.

The system has fast transient response and low current mismatch, but requires external controller. The system also requires multiple connections between the controller and each power supply, so it is better to use digital control bus.

D. Automatic load share, average current

Automatic load share needs no external controller or master device. This technique needs load share bus that is connected to each module and amplifier that compares value on load share bus with individual current of power supply and adjusts reference of voltage amplifier until the currents becomes equal thus achieving equal load current distribution.

There are two methods of automatic current share: average current share and highest current.

The average current method is patented method [3]. Current monitor of power supply drives common load share bus via a resistor. Load share bus is node where all resistors are connected, so it represents average value of currents. Current adjust amplifier senses difference on the resistor and adjusts reference of voltage amplifier to make the difference equal to zero. This method achieves accurate load sharing but cause certain problems described in [2].

E. Automatic load share. Highest current method.

This technique is similar to previous but resistor is replaced with diode. Thus a power supply with highest current becomes master and drives load share bus while other power supplies becomes slaves. This method provides accurate load sharing for slaves with error for master caused by the diode.

III. Analog Methods. Detailed Analysis

Highest current automatic load share is one of most common load share technique. This method is very flexible and may be used in various situations. TI, Linear, Fairchild manufactures IC for load share. Basic scheme is presented in fig. 1. The current monitor drives load share bus via the diode. Power supply with highest current becomes master and catches the load share bus. Current monitors of other devices are disconnected from load share bus by reverse biased diodes, so the devices become slaves. Current adjust amplifiers adjusts reference voltage of voltage amplifier thus adjusting output current of power supplies. In case of shutdown or overcurrent of power supply it is disconnected from load share bus by diode. If load share bus is shorted all power supplies goes into standalone mode. The system will be able to work with shorted load share bus but power supplies have to have constant current limiting mode. Then with disconnected load share bus output voltage will stay, though current misbalance will be significant.

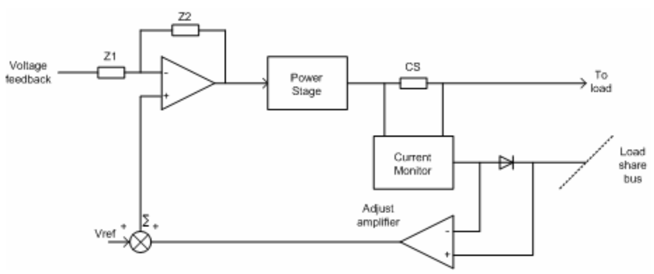

Fig. 1. Automatic load share, highest current. Output current of Power stage is sensed by current sensor CS and current monitor. Adjust amplifier adjusts voltage reference for feedback amplifier.

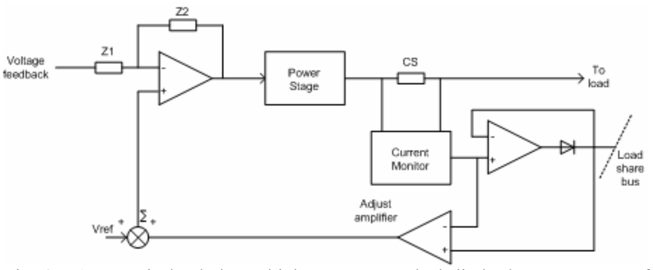

Fig. 2. Automatic load share, highest current. Ideal diode decreases error of master power supply.

To decrease current error of master module the diode between current monitor and load share bus is replaced with an amplifier as an ideal diode, as it shown in fig. 2.

This scheme performs very well in custom made power supplies. If we use of-the-shelf power supplies this scheme also quite useful. We need power supply with remote voltage sense input. This input is designed for compensation of voltage drop across wires and connectors. Detail of the technique is described in [4] [5], the scheme shown in fig. 3.

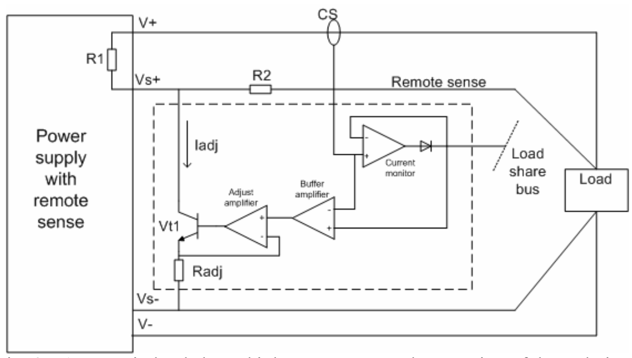

Fig. 3. Automatic load share, highest current. Implementation of the technique for ready to use power supplies.

Resistor R1 internally connects output of power supply to remote sense input. This is a needed feature in case of disconnection of remote voltage sense. Positive remote voltage sense of the power supply must be connected to point of load via small resistor R2. Adjust amplifier sets collector current of VT1, Iadj, and this current decrease voltage at input Vs+ of power supply thus forcing power supply to increase its output voltage and output current.

Automatic load share method needs one extra feedback loop with crossover frequency less than 1/5 of crossover frequency of voltage loop. This means degradation of transient behavior of the system. It is shown [1], that transient voltage drop at current step-up is bigger in systems with automatic current sharing that without them. Feature of automatic loadshare system is that at periodic load steps there is some special beat-frequency and dynamical current misbalance becomes unacceptable thus system get into fail.

There are lots of publications [2] [5] [6] [7] [8] devouted improving dynamical response of parallel system, but it is possible in narrow bandwidth.

Analog load share bus is cheap and efficient solution for system with relatively slow load changes. Fast and/or periodical load steps may cause system fault.

IV. Digital methods

Digital control of power supplies becomes more common due to its advantages. Digital approaches have an ability to implement sophisticated control algorithms and advanced filters. Design can be easily upgraded to meet new specifications or technologies. Environmental variations and EMI noise are of a lesser impact on digital compensator and logic, thus designs may be optimized for high performance not for worst-case conditions stability.

A digital load share technique explores the same methods of load share: master-slave technique and automatic technique.

An example of digital master-slave current share techniques is described in [9]. The digital PWM technique is used for current sharing obtaining perfect matching of duty cycles of PWM signals among different modules. The approach requires tight matching of gate driver delays and power stage components among the phases.

Digital master-slave current share system that uses multiphase approaches are described in [10 – 12].

In masterless system identical power supplies are connected in parallel to supply load current. For they are identical all of them provides identical information to digital load share bus, and calculate required output current. In [13] is described masterless digital load share technique. Controller Area Network (CAN) is used as digital bus. Each module periodical broadcasts packet of data over bus. So for N power supplies each module (N-1) times receives data and for current averaging N currents must be stored in memory.

CAN bus is one of the Collision Resolving buses. Data on CAN bus consist of dominant and recessive bits and during transaction transmitter senses bus. If the transmitter sends recessive bit but there is dominant bit on bus then transmitter lost bus and back off [14]. This guaranty that transaction with high priority will be sent. But there is risk of long delay or even lost of transaction with low priority. For this system some algorithmic tricks must be used to prevent lost of one of power modules data.

CAN data frame is relatively long, and includes 44b of service information. For 8b of data frame which means 0.4% accuracy, packet of data has 52b and for transfer rate of 1Mbit/s we have 52us for one packet or frequency 19200Hz. So four devices broadcast their data for 208us, i.e. frequency is 4807Hz. This seriously limits transient response of current averaging system and calculation pipeline cannot improve it.

In [15] masterless system called Digital chain is described. The chain control algorithm reduces amount of data needed to calculate average current.

In pipeline calculation each power supply calculate average current once per cycle. So for i-th cycle average current calculated by 1-st module is

$$Iave[1](i)=[I[1](i)+I[2](i-1)+I[3](i-1)+ .. +I[N](i-1)]/N \quad (1)$$

where Iave[1](i) is average current, calculated by 1-st power supply on i-th cycle of operation, I[1](i) – output current of 1st power supply on i-th cycle of operation, I[N](i-1) – output current of N-th power supply on (i-1) cycle of operation and N – number of power supplies. From here it is easy to obtain that on j-th cycle average current is

$$Iave [i] = Iave[i-1] - I[i][j-1] / N + I[i][j]/N, \quad (2)$$

where Iave[i] is average current, calculated by i-th module, Iave[i-1] – average current, calculated by previsions power supply, I[i][j −1] – output current of [i] power supply at [j-1] cycle and I[i][j] is actual output current of i-th power supply.

Thus only calculated average current and two values of output current of power supply must be stored in memory. Volume of required data and calculation does not depend on number of power supplies connected in parallel.

In steady state digital chain shows good results. At load step average current must be adjusts to actual load current and this takes at list N cycles. Addition digital filter is proposed in [15] to improve transient response. The additional digital filter turns off digital chain control at load steps.

It is not mentioned in [15] but the Digital chain isn't completely masterless solution. The digital chain is workable only if average current is calculated in certain sequence and N in (2) must meet actual number of power supplies. External controller must handle events like power down of one of the power supplies or hot swap.

The conclusion is that digital approaches have the same division into master-slave architecture and automatic architecture. Master-slave architecture has better transient response. Automatic architecture needs external feedback loop and has slower transient response but guarantied redundancy. Transient process at hot swap or power down of one module in parallel power supply system is poorly described in known publications.

V. Algorithm of automatic master selection

The charge of the article is combine advantages of automatic and master-slave approaches with focusing on problem caused by hot swap events.

We need power supply system that consists of identical modules with hot swap ability with no dedicated master device and with no external current adjustment loop.

In this article we propose digital system with automatic master detection algorithm.

In analogue current share with highest current adjustment power supply with highest current becomes master. In digital systems this approach is not acceptable for we needs to collect data from every power supply and this takes lot of time.

It was mentioned above that CAN protocol has collision resolving and device with higher ID holds the bus. We may use this feature for automatic master selection: device with highest priority will be master, over will be slaves. If master goes into power down power supplies start arbitration procedure and again device with highest ID becomes master.

Identification (ID) field in CAN frame having 11bit length does not allows usage of serial number of a power supply as unique ID. PCI-bus based computer system like cPCI or VME uses geographical address (GA) signals to program ID of device. These signals have two states: connected to common node (ground) or disconnected. The GA signals set unique ID of power supplies and master/slave status of a power supply depends on slot it is inserted. We use this approach in our system. Power supplies are inserted into a power supply rack with GA signal set for each slot.

A master device controls slave devices by setting their output mode. This approach performs well with current mode. So the master device sets the current of slave devices. Then only output voltage and number of slave devices is required for master device to calculate current. Voltage compensator must be adjusted to number of parallel connected power supplies.

Master detection subroutine of power supply works in three modes: power-on master detection, steady state work and master redetection.

At power-on power supply examines its GA input and determines its ID. Then power supply sends request for other power supplies on bus. If the power supply loose arbitration, receives answer from power supply with higher ID, or receives request from power supply with higher ID then it goes into slave operation mode. In other cases it goes in master operation mode. Master power supply finalize polling IDs to determine number of parallel connected devices and adjust its voltage compensator. After this output voltage may be applied. Master device broadcasts output current for all devises and periodically polls slave devises to control number of them.

Slave device senses the bus for master's command and requests. If slave device does not receive commands for certain time it starts procedure of master detection which is similar to power-on procedure but output voltage is presence at output of a power supply.

Let us find transfer function of parallel connection of n identical power supplies with common control. Power stages are identical mismatch in parameters as voltage and current mismatch is negligible. Then for n identical power stages with transfer function Wps total transfer function will be n*Wps. Thus only correction of amplification of voltage loop is needed to adjust voltage feedback loop to actual number of power stages. When one of power stages switches off then from this moment until the moment when master device detect changes in power stages and adjusts voltage feedback loop power supply may run into oscillation. We investigate a MathLab model of power supply to test the operation of power supply at power off event.

MathLab model of 5kW power supply was investigated. As power supply we took full bridge power supply with average

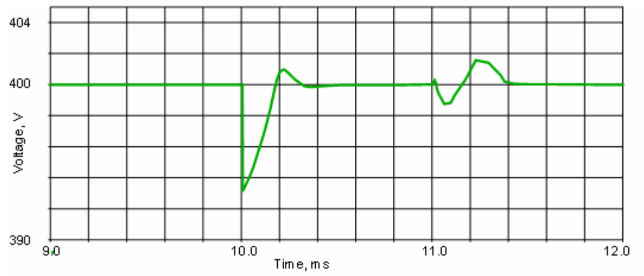

Fig. 4. Results of MathLab modeling of DC/DC converter with automatic master detection. Output voltage of DC/DC converter.

current mode control. Input DC voltage of power supply was 420V; output DC voltage was 400V and switching frequency was 100 kHz. We modeled situation of power down of one of power supplies. In MathLab model three power stages were connected to 8kW load. Voltage loop is common for them. We disconnected one of power supplies from load at 10ms and after 1ms delay (i.e. at 11ms) we adjusted voltage loop to actual transfer function. Time diagrams of the experiment are presented in fig. 4. It is seen that voltage spikes at transient does not exceed 2%. Transient process is short and voltage distortions are acceptable. Increasing of number of power stages decreases influence of power down of one stage.

CAN bus looks like preferred bus for digital load share bus for it has all necessary features including hardware CR and arbitration. But CAN data frame is relatively long: 11bits for ID field, 15bits of CRC looks excessive for power supply applications. CR may be built in I2C-based buses but standard configuration of I2C-bus and PM-bus is master-slave so functions and features needed for CR have to be realized by software.

Power supply with parameter described above and CAN-based load share bus is under development at Siemens.

VI. Conclusion

There are two approaches to load share in power supplies. First is master/slave approach and second is automatic approach. Master/slave load share techniques show outstanding accuracy and good transient response but poor redundancy. Master/slave approach is preferred in digital realization of load share

Automatic approach shows good accuracy in steady state but slow transient response. Techniques with analog load-share bus commonly use automatic approach. Automatic digital load share bus with average current adjustments needs some algorithmic tricks to make transient response faster.

Digital load share technique with automatic master detection is proposed in the article. This technique combines advantages both of master/slave and automatic approaches. MathLab model shows good performance of automatic master detection at hot plug events.

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